

CONSTELLATION X-RAY MISSION AND SUPPORT

**NASA Cooperative Agreement NCC5-368
Final Report
For the Period October 1, 1998 to October 14, 2004**

**Principal Investigator
Dr. H. Tananbaum**

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**National Aeronautics and Space Administration
Goddard Space Flight Center
Greenbelt, Maryland, 20771**

**Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts, 02138**

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The NASA Technical Officer for this Agreement is Jean Grady, 740.0, NASA/Goddard Space Flight Center, Greenbelt, Maryland 20771-0001

1.0 Introduction

This Final Report summarizes work performed by the Smithsonian Astrophysical Observatory (SAO) for NASA Goddard Space Flight Center (GSFC) under Cooperative Agreement NCC5-368¹. The Agreement is entitled "Constellation X-ray Mission Study and Support." The report covers the full duration of the Agreement which ran from October 1, 1998 to October 14, 2004. Included in the report is a description of previously unreported work that was performed between October 2003 and the end of the Agreement. For convenience, the previously unreported work is covered first in Section 2.0. Then, an overall summary of all work performed under the Agreement is presented in Section 3. Section 4.0 contains a list of all formal reports that SAO has submitted to GSFC along with publications and presentations at various conferences.

Throughout the life of the Agreement, work carried out by SAO was under the overall direction of Dr. Harvey Tananbaum, the SAO Principal Investigator for the program. Mr. Robert Rasche was the SAO Program Manager and was responsible for day-to-day program management at SAO and for management coordination with GSFC.

As is appropriate to a Cooperative Agreement, SAO worked with GSFC in an integrated team mode. SAO was involved in the overall mission management, technology development, scientific direction, and mission definition. While formal overall management responsibility resided with GSFC, scientific lead and subordinate responsibilities were shared by GSFC and SAO.

The work performed by SAO was consistent with the SAO proposal "Constellation X-ray Mission Study and Optics Development" dated September 1997, which was the basis for establishing the subsequent Cooperative Agreement. Over time, the scope of the effort was expanded somewhat to accommodate the needs of the project. Work, except for meeting support and high priority program tasks, was at a level of effort.

Priorities and work progress were closely coordinated with the Constellation-X Project management at GSFC. During the period of performance of the Agreement, SAO supported nine major areas of activity. These areas related to:

- Constellation X-ray Mission Facility Definition Team and Study Management
- Science Support
- Spectroscopy X-ray Telescope (SXT)
- Systems Engineering
- Travel in Support of the Work Effort
- In-house Management and Coordination
- TRIP Report and Follow-up
- Industry Liaison
- Constellation-X – XEUS Collaboration Consideration

¹ In subsequent text, NCC5-368 is simply referred to as the "Agreement". A Cooperative Agreement is the appropriate vehicle for the close, flexible, and wide ranging interaction between SAO and NASA needed to ensure the success of the Constellation-X project formulation activity.

Questions regarding this report can be directed to:

Robert W. Rasche

Smithsonian Astrophysical Observatory
60 Garden St., MS 29
Cambridge, MA 02138
(617)-496-7774
rrasche@cfa.harvard.edu

2.0 Report for Period October 1, 2003 – October 14, 2004 (not reported previously)

2.1 Areas of Activity

SAO performed work in eight major activity areas. These areas related to:

- Constellation X-ray Mission Facility Definition Team and Study Management
- Science Support
- Spectroscopy X-ray Telescope (SXT)
- Systems Engineering
- Constellation-X – XEUS Collaboration Consideration
- Travel in Support of the Work Effort
- In-house Management and Coordination
- Limited and Informal Industry Liaison

2.2 Constellation X-ray Mission Definition Team and Study Management

2.2.1 General Study Management and Coordination

SAO continued to be heavily involved in Constellation-X mission definition and the overall management of the study. Management decisions continued to involve the Project Scientist, Dr. Nicholas White (GSFC), the Facility Science Team Chairman, Dr. Harvey Tananbaum (SAO)², the Project Manager Ms. Jean Grady (GSFC), and the SAO Program Manager, Mr. Robert Rasche. Frequently the two Mission scientists, Dr. Jay Bookbinder (SAO) and Dr. Robert Petre (GSFC) were also involved. Dr. White was frequently assisted or represented by the Deputy Project Scientist, Dr. Kimberly Weaver of GSFC and towards the end of the period by Dr. Ann Hornschmier (GSFC).

SAO had a significant role in the technical overview, planning, and review of both future work and work in progress with particular emphasis on the SXT Mirror Assembly.

SAO was also heavily involved in the management of mission definition activities, particularly with regard to thermal control, error budget development, and developing both science and top level mission requirements as well as the many related flow-down requirements. SAO personnel brought extensive and relevant experience from CHANDRA, HEAO, TRACE, HST, and other programs to the Constellation-X mission definition work.

Drs. White and Tananbaum had primary responsibility for scientific management with support from Drs. Bookbinder (SAO), Weaver (GSFC), Petre (GSFC), Hornschmier (GSFC), and Garcia (SAO) and, occasionally, others. This included coordination with members of the Facility Science Team, interactions with NASA Headquarters and the scientific community at large, as well as participation in the Constellation-X Study Team meetings that were held approximately every two weeks at GSFC. Other special meetings were also supported.

² Because Constellation-X is a consolidation of their individually proposed and accepted programs into a single program, Drs. White and Tananbaum function as equal Co-Principal Investigators although they have well-defined and separate formal responsibilities.

2.2.2. Technology Development Management and Coordination

Under the Agreement, SAO had an important role in managing and coordinating technology development for Constellation-X. That role continued through the reporting period.

SAO's main technology management involvement has been related to the SXT X-ray mirror and the reflective gratings. However, SAO has also kept involved with and informed of instrument technology developments and related planning and budget negotiation. Since the IPT funding comes through GSFC contracts, the SAO role has been primarily to provide expertise, coordination, and general overview to the instrument development work. SAO supported essentially all of the project teleconferences related to mirror technology and most of the telecons related to instrument technology.

During the reporting period, meetings were held among GSFC, SAO, MIT, and the U of Colorado to discuss both technical and management issues related to the so-called "off plane" grating concept. Dr. Reid (SAO) worked closely with Dr. Flanagan (MIT) in establishing formal requirements and allowable errors.

2.2.3 Reports and Presentations

SAO personnel developed and made presentations at many meetings. These meetings included the biweekly team meetings at GSFC, and related splinter meetings, as well as technical interchange meetings (TIMs). The TIMs have generally been related to work on the SXT Optical Assembly Pathfinder. SAO (Podgorski and/or Reid) made presentations at the monthly SXT Mirror Status Meetings.

2.2.4 Mission Studies

SAO personnel also made direct technical contributions to the ongoing mission studies at GSFC and to discussions and trades related to mission operations and instrument accommodation. This helped ensure that relevant CHANDRA (AXAF) experience (which is ongoing) in these areas was transferred to the Constellation-X program in an effective and continuous way. These contributions have tended to be related to systems engineering issues — an SAO strength (see Section 2.5).

2.2.5 Coordination with Industry

SAO staff were involved in a number of project management interactions between the Constellation-X project and industry. These interactions were both formal and informal. The objective has been two-fold:

- To help industry maintain a continued awareness of relevant technologies and interests.
- To encourage interest in the Constellation-X project on the part of industry.
- To establish useful IR&D programs of benefit to Constellation-X.
- To ensure that industry concerns were represented in project planning.

Because of overall project funding cuts and a significant delay in projected launch date, industry interest in Constellation-X was noticeably reduced during the past year. Nonetheless, SAO helped to maintain industry awareness and some level of interest using existing and generally long-standing contacts with industry staff and management, particularly at Ball Aerospace, Zeiss, NGST, and Lockheed-Martin.

2.3 Science Support

2.3.1 Chair of the Facility Science Team (FST)

Under the Agreement, SAO provided the Chair of the Constellation-X Facility Science Team which is the group of scientists who help guide the program with regard to scientific objectives and needed capabilities. Dr. Tananbaum served as Chair and was assisted by the Mission Scientist, Dr. Bookbinder and by Dr. Garcia and other members of the FST from several institutions and, of course, the Project Scientist, Dr. White and his science colleagues at GSFC.

Dr. Tananbaum was a point of contact for both general FST members as well as for the leaders of the instrument technology teams. This activity was closely coordinated with Dr. White at GSFC who carried out a similar function. In general, Dr. White was more involved with the Government members of the FST and Dr. Tananbaum worked with FST members from non-Government organizations.

2.3.2 Mission Scientist

As required by the Agreement, SAO provided the expert services of Dr. Jay Bookbinder who filled the position of the Mission Scientist from SAO. His GSFC counterpart is Dr. Robert Petre.

Dr. Bookbinder participated in team meetings at GSFC and SAO and was an active and direct technical contributor to the SAO team. He also carried out special assignments for the FST Chair, Dr. Tananbaum. Dr. Bookbinder brought substantial and relevant expertise and experience from TRACE, the ongoing Solar-B, SDO/AIA, and other NASA programs. Working with others, he continued to further define and document the Constellation-X Top Level Requirements. A significant amount of both analysis and coordination with others was required to carry out this activity. Dr. Michael Garcia of SAO provided significant support to Dr. Bookbinder in Bookbinder's role as Mission Scientist.

2.3.3 Facility Science Team Meetings

SAO and GSFC provided substantial support to Dr. Tananbaum and others in planning and conducting an FST meeting at GSFC (off site) on November 19-20, 2003. A subsequent FST meeting was planned and held at SAO on October 14, 2004 (the last day of the Agreement) and on October 15, 2004.

Work during this reporting period involved close out of actions arising out of the September 2002 FST meeting and planning and carrying out an FST Meeting the was held at Columbia University during May 2003. SAO also participated in preliminary planning for an FST meeting at GSFC for Fall 2003.

2.4 Spectroscopy X-ray Telescope (SXT)

During the reporting period, SAO performed SXT-related work in six main areas:

1. SXT Management and Coordination
2. SXT Mirror Module Design
3. SXT Mirror Assembly and Alignment Studies
4. SXT Error Budget Development
5. Segment Mirror Mandrel Procurement
6. Flight Mirror Development Planning

2.4.1 SXT Management and Coordination

Working with the concurrence of the Project Management, SAO provided extensive oversight and direction to the Constellation-X SXT mirror definition and development. This activity included but was not limited to:

- Participation in numerous status review and planning teleconferences
- Informal tracking of SXT work progress at MSFC, GSFC, and SAO
- Evaluation and informal reporting of progress to GSFC Constellation-X project office.
- Development and evaluation of work plans and budgets
- Formulation and presentation of recommendations for future plans and priorities
- General overview of SXT work

2.4.2 SXT Mirror Module Design

SAO continued in-house concept and analysis studies related to SXT segmented mirror concepts. William Davis (SAO) provided essentially all of the precision structural analysis support to the ongoing work. In this role, Davis worked closely with his GSFC counterparts and participated in telephone conferences and on site meetings at GSFC.

As work on the OAP and subsequent designs progressed, SAO tracked and helped to evaluate the technical progress. This overview provided independent assessments and recommendations to the GSFC Project Manager.

A low level effort was continued to evaluate technologies other than epoxy replication. The basic notion is to form smooth glass and then machine the final figure into the substrate without excessive degradation to the surface finish. Such an approach, if feasible, might produce a reflector having better resolution than can probably be obtained using epoxy replication. In this context, both ion polishing (figuring) and MRF technology were evaluated. This work received low priority because of more pressing demands on resources. By the end of the Agreement, results were, at best, inconclusive and not particularly encouraging. A significant effort will be required before objective conclusions can be drawn.

2.4.3 SXT Mirror Assembly and Alignment Studies

A new Constellation-X Centroid Detector Assembly (CDA) was completed and delivered by Bauer Associates. The work was performed under a subcontract to SAO. Dr. Podgorski (SAO) served as Technical Officer.

2.4.4 SXT Error Budget Development

Work on the SXT error budget continued during the reporting period although because of both personnel and funding conflicts, the effort was somewhat limited. Nonetheless, substantial progress has been made. This was facilitated by the close working relationship that has now developed between Drs. Podgorski (SAO) and Dr. Saha (GSFC) who are both involved in the development of the error budget. They have tended to take different approaches which when their analyses produce equivalent results (they usually do) provides an important check on the work as a whole.

SAO also developed an error budget for the OAP assemblies and related test set-ups.

2.4.5 Segmented Mirror Mandrel Procurement

SAO participated in the overview of mandrel development work at Zeiss that was carried out under a MSFC contract. SAO participated in monthly status meetings and reviewed contract documentation. The third of three mandrels was completed and delivered to MSFC. SAO was

also involved in some subsequent procurement planning for forming mandrels. Rasche (SAO) has been most involved in this effort and in helping to coordinate and effective and cordial interface with Zeiss.

2.5 Systems Engineering

SAO continued to provide systems engineering support to the Constellation-X project. Work was concentrated in seven main areas:

- Thermal control
- Requirements and requirements flow down development
- Opto-structural analysis of segmented SXT concepts
- System error budgets
- Evaluation of Collaborative Mission Concepts
- Glass Strength Testing

2.5.1 Thermal Control

SAO and GSFC continued to work together in the areas of both instrument and overall system thermal control. In particular, Freeman (SAO) continued to review the various system configurations as they were put forward. Effort by SAO in this area was limited primarily by available funding and staff availability. SAO continued work related to SXT Mirror Assembly temperature control. SAO also performed steady state and transient analyses of the hot forming environment with emphasis on identifying and controlling gradients and establishing the driving characteristics.

2.5.2 Requirements and Requirements Flowdown

The Constellation-X Top Level Requirements have been defined although a few of them may be modified. Recent work continued to focus on flow down requirements on the various Constellation-X subsystems. This work was done at SAO mainly by Drs. Bookbinder and Podgorski with assistance from Drs. Reid and Garcia. This work included analysis and research related to establishing numerical values for the various requirements.

2.5.3 Opto-Structural Analysis of Segmented SXT Concepts

As indicated in Section 2.4.2 SAO provided optical and structural analysis support to the various mirror assembly concepts. SAO also was involved in the systems optical and structural engineering related to the Constellation-X gratings.

2.5.4 System Error Budgets

Some work was done during the reporting period to extend system error budgets. That more work was not done in this area was due mainly to funding limitations. In addition to the reference error budget calling for 15 arc-second overall telescope resolution which was somewhat expanded, a new error budget for a telescope having overall resolution of 5 arc-seconds (HPD) was completed at top level.

2.5.5 Evaluation of Collaborative Mission Concepts

During the last half of the reporting period, SAO was very involved in examining the notion of a consolidated XEUS-Constellation-X mission. Initial work related to better understanding the ESA micro-pore optics fabrication, configuration, and performance estimation.

SAO was heavily involved in preparing for an informal meeting in August 2004 with Lumb and Bravdaz of ESTEC. This meeting was preceded by a plenary meeting where concerns and limitations on transfer of information were discussed frankly, but amicably. The actual meeting was extremely productive and served to establish a good relationship at the working level that continues to today.

Drs. Reid and Garcia (SAO) started stray light studies for both the ESA 50 meter focal length configuration as well as other configurations. SAO also participated in definition and preliminary studies of other configurations.

2.5.6 Glass Strength Testing

Reid (SAO) and others at GSFC organized and planned a program to test the strength of the glass base lined for use as reflector substrates. The program was started, but was interrupted due to lack of funding and only recently has been restarted. There are no formal conclusions at present, but there have also been no real surprises.

2.6 Travel

The Agreement provided funding for frequent program travel. Most, but certainly not all, of the travel was between SAO and either GSFC or MSFC.

With few exceptions, a Constellation-X Study Team meeting was held at GSFC every other week between 1:00 p.m. and 3:00 p.m. with splinter meetings on either side of this fixed time. This arrangement allowed SAO personnel to travel from Boston to GSFC and return on the same day with substantial savings in lodging and per diem costs. These meetings were usually attended by at least one SAO person and occasionally by three or four if required by either the meeting agenda or related splinter meetings. Whenever possible, splinter meetings were set up on the same day as the team meetings. These meetings were usually technical interchange meetings that took the form of informal working meetings. However, some of the splinter meetings were management review and planning meetings.

Travel also included on-site discussions with Zeiss by Rasche (SAO) and Drs. Petre and Zhang relative to plans for future flight work. A NASA presentation was made to Wilhelm Egle who has managed the Constellation-X work at Zeiss and who has retired.

2.7 In-House Management and Coordination

In addition to direct participation in the Constellation-X project summarized above, SAO carried out housekeeping, coordination, and planning activities at SAO. This work related mainly to the orderly operation of the SAO Constellation-X team.

These activities included:

- Cost planning, tracking, analysis, and control
- Time keeping
- Personnel evaluation inputs
- Purchasing and logistics
- Coordination and information meetings
- Travel arrangements

SAO did not produce any stand-alone formal documents as such during the period of performance. Analyses, error budgets, area vs. energy plots, and requirements were developed

and documented as informal documents, particularly by Drs. Bookbinder, Podgorski, Reid, and Garcia at SAO. These were distributed in a timely way as attachments to e-mail messages. The Constellation-X Top Level Requirements document and its companion Flow Down Requirements document are still in process and will, in any event, be released as project documents. Of course, the most significant document produced was the TRIP report.

3.0 Summary of All Work Performed under Cooperative Agreement

This section summarizes work performed under the Agreement during its lifetime. Emphasis is given to significant events, changes in approach during the work, and changes in SAO personnel supporting the work. The reader should understand that much of the work performed was done jointly as a GSFC-SAO team and in some areas, particularly with regard to SXT mirror technology, by a GSFC-SAO-MSFC team. Consequently, SAO does not claim to have done all the work performed in the various areas of activity. Where possible, we have tried indicate the portion of the work carried out by SAO staff, but we have also tried hard to keep the overall narrative intact.

SAO work can be grouped into seven areas. These are:

1. SXT Mirror Technology
2. Science Planning and Management
3. Top Level and Flow-down Requirements Definition and Error Budgeting
4. Mission Studies
5. TRIP Report
6. Industry Liaison
7. Collaboration Considerations

3.1 SXT Mirror Technology

The state of mirror technology at the beginning of the Agreement was an approach using ultra-thin electroformed nickel shells for the Constellation-X mirror assembly. This was based on both the XMM experience and upon independent technology that was under development at MSFC and looked promising. MSFC was also fabricating large aluminum mandrels on which to electroform the thin nickel shells. The structural advantages of a closed shell were (and are) apparent *provided* the electroforming process does not leave residual deforming stress in the thin shells. SAO provided technology and project management overview to this work.

It was decided to augment the MSFC mandrel effort by purchasing a similar mandrel from industry. SAO helped to prepare the RFP and provided consultative support to MSFC in evaluation the bids. The result was that a FFP subcontract was awarded to Carl Zeiss of Oberkochen, Germany to fabricate two cylindrical aluminum mandrels having a Wolter I surface of revolution along the center axis. SAO participated in the kickoff meeting, monthly progress reports, and an on-site meeting in Oberkochen.

3.1.1 Moving from Electroformed Nickel to Segment Technology

The Constellation-X configuration was initially based on using six Delta II rockets and mirror assemblies whose outer diameter was 1.2 meters. Because of projected launch costs for the Delta II (and concerns about availability), the baseline was changed to four independent telescopes launched on two larger rockets. In order to maintain essentially the same effective telescope collecting area, a new preliminary telescope design was developed by SAO (van Speybroeck). This resulted in a "constellation" of four mirror assemblies, each having a nominal outside diameter of 1.6 meters. The downside of this was the need for larger mandrels on which the outer diameter shells could be formed. No interested industrial source for these larger mandrels could be found including Zeiss who felt the mass of the mandrels alone would cause problems. SAO took the lead in looking for sources who were interested in producing these larger mandrels, but

was unsuccessful in finding a potential source without embarking on a long and expensive development program of uncertain outcome.

Work had been preceding at GSFC along a parallel path using a concept involving so-called segmented optics. Here, a given shell is broken up into azimuthally curved segments which when assembled complete the required cylinder less interconnecting structure. Work at GSFC had concentrated on the technology associated with making the individual segments, while Cohen (SAO) and Shattenburg (MIT) had developed a concept for mechanically mounting and aligning the formed reflectors. This approach, including the assembly build up process, was documented by SAO in some detail.

Because of substantial progress in segmented mirror technology (although it had lower priority than the electroformed nickel shell approach) and the perceived difficulty in obtaining large cylindrical mandrels needed to make full shells, the project emphasis was changed from the electroformed nickel shells to the segmented mirror approach. This work on segmented mirror technology has continued and is now the primary NASA approach.

The use of segments changed the mandrel requirements from large (and heavy) cylindrical units to slabs having the desired optical contour on one surface. It was decided to obtain precision replication mandrels and a competitive subcontract was let by MSFC to Carl Zeiss for the fabrication of three precision mandrels representing an outer, a middle, and an inner segment. The mandrels are made of Zerodur and have both the parabolic and mating hyperbolic optical surfaces on them with a narrow axial separation between the two surfaces. SAO supported the SEB and the subsequent monitoring of the work at Zeiss. As the work progressed, parallel work by GSFC, SAO, and Zeiss made it clear that because of independent adjustment capability, the parabolic and hyperbolic surfaces do not have to be on a common mandrel and, in fact, the parabolic mandrels and the hyperbolic mandrels can be made on separate pieces of glass. This greatly simplified the process and separate mandrels became the basis for flight program planning that was then beginning.

At the start of the segmented design work, it was assumed that the formed reflector need not be too precise and that the replication process where epoxy is used to transfer a gold or other coating to the formed reflector would be adequate to correct the figure. This did not turn out to be the case. Cohen at SAO showed by detailed modeling that:

- Epoxy shrinkage effects might distort the final reflector beyond allowable limits unless very thin and quite uniform epoxy depositions were used.
- Regardless of epoxy thickness, unless the formed reflector was supported during the replication process, the epoxy would tend to take the formed shape of the reflector upon curing.

This meant that the formed reflector substrate could not be deformed during the replication process, e.g. by pushing on its back side to ensure good contact with the epoxy. One consequence of this was that efforts at GSFC where the experimental work was going on, focused on ever-thinner epoxy mixtures with promising results. The other consequence was that it was realized that the figure on the forming mandrels had to be essentially as good as that on the replication mandrels. A serious consideration of suitable materials for forming mandrels was begun. SAO (Cohen, Reid, and Rasche) participated in the search for optical material which could take a high precision optical figure and finish and also be heated to around 700°C without adverse effects on material properties. This entailed discussions involving SAO, GSFC, Corning, and Zeiss and Schott in Germany. This search ultimately although not immediately, identified three candidates – Keatite (Schott proprietary ceramic), fused silica, and possibly ULE. Rasche made several trips to Germany to discuss possible materials as well as partake in developing flight program planning information (see Section 3.5 TRIP Report).

3.1.2 Beryllium Reflector Technology

In parallel with the development of glass segment technology, a limited effort was carried out by Cohen at SAO to evaluate the use of thin beryllium sheets as reflector substrates. This was apparently feasible because of a fabrication technique that did not leave residual stress in the curved sheets. Initial analysis showed the approach to have acceptable cost and schedule characteristics. The potential advantages of the technology included:

- Beryllium would be stiffer with corresponding less effect from epoxy shrinkage
- The higher thermal conductivity of beryllium might be an advantage relative to mirror assembly thermal control
- Beryllium would be substantially stronger for a given thickness and while brittle, probably would be preferable to glass.
- The fixturing scheme proposed would not strain the substrate excessively during replication which, in turn, would allow the use of less precise substrates.
- The process would only require replication mandrels because the initial substrates were machined in a hot form and allowed to anneal and cool to the approximate curvature dimension desired (tolerance of ± 0.05 mm)

Using one of the cylindrical mandrels made by MSFC, Cohen with much assistance from MSFC carried out several replication experiments at MSFC. The main problems were getting complete epoxy coverage and some fixture distortion which put strain on the reflector during replication. The results were somewhat inconclusive although each result appeared to be better at least in terms of epoxy issues than its predecessor. Mainly due to lack of available project funding which did not allow for parallel technology, this work was set aside and never resumed.

3.1.3 Optics Lead

Early work on the Constellation-X mirror assembly technology benefited greatly from the incisive and objective review and guidance from Dr. Leon Van Speybroeck who had led the overall mirror assembly effort on Chandra and in no small way was responsible for its great success. Regrettably, Dr. Van Speybroeck died in December of 2002. SAO was fortunate to recruit Dr. Paul Reid who has taken the Constellation-X optics lead. Dr. Reid led the Chandra optics fabrication effort at what was then Hughes Danbury and is a recognized X-ray mirror fabrication and design expert in his own right. He has been active in almost all phases of the Constellation-X mirror assembly optics and related technology and metrology as well as establishing error budgets and requirements.

3.1.4 Deflection Effects Analysis

One of SAO's important roles was analyzing reflector deformations due to support schemes and statically indeterminate forces as well as predicting the performance degradation resulting from such deformations. Analysis also included studies of 1 g effects and concepts for supporting single reflectors to obtain good metrology data.

As a corollary, SAO also analyzed the effects of various assumed temperature gradients across reflectors, first by calculating deflections and then by calculating optical response. In this way, temperature control requirements for the Constellation-X mirror assembly were bounded.

3.1.5 Centroid Detector Assembly (CDA)

The Chandra program had developed a sensitive mirror assembly and alignment tool called the Centroid Detector Assembly (CDA). This assembly was already in use at SAO on another program (SOLAR-B). A subcontract was let by SAO to Bauer Associates to analyze how well the CDA might work on the Constellation-X mirror assembly and what modifications might be needed to enhance its performance. As it turned out, some alternative optics and support structure

were needed together with some electronic and software modifications that were of use to the other SAO program. These changes were made, and the unit was satisfactorily tested. It was used to assemble and align the OAPs on a non-interfering basis with Solar-B. The test indicated that some further improvements would be beneficial. A second unit to be dedicated to Constellation-X was built and commissioned and is in use today.

3.1.6 Optical Assembly Pathfinders I and II

The Constellation-X Project established a technology program with related milestones and schedules to develop and demonstrate the segmented mirror technology. A key element of this program, and one which was implemented, was the Optical Adjustment Pathfinder (OAP) which was a fixture designed to hold a pair of reflectors in mutual alignment for test. SAO was involved in the review of the design and made many recommendations. The main objective of the first unit was to learn how to handle the glass reflectors while they were being aligned and to learn how to effectively use the CDA. These objectives were realized. Based on this experience, a second unit was designed and built. The main objective was to develop a test procedure for X-ray testing at MSFC and trouble shoot and verify that procedure. SAO participation in this activity was extensive. Contributions included the lead role in developing the test specification, design and fabrication of a controlled temperature chamber for the OAP, and the development of a governing error budget.

3.1.7 Telescope Effective Area vs. Energy

SAO (Podgorski and Freeman) performed most of the Constellation-X effective viewing area calculations for the various configurations studied at one time or another during the life of the Agreement. These calculations included areas for both reflective gratings and micro-calorimeter instruments and were almost always performed as a function of incident X-ray energy (wavelength).

3.2 Science Planning and Management

SAO was heavily involved in both science planning and science management. As noted elsewhere, Dr. Harvey Tananbaum has been Chair of the Constellation-X Facility Science Team during the entire life of the Agreement. During this period, Dr. Jay Bookbinder has been one of the two Mission Scientists on the program and has worked closely with Dr. Tananbaum on these activities. More recently, Dr. Michael Garcia has transitioned from the Chandra project to Constellation-X and is complementing Dr. Bookbinder. The goal has been to have two FST meetings each year, alternating between GSFC and SAO. Over the life of the grant, this objective has generally been met.

In addition to planning, coordinating, and carrying out the FST meetings, SAO scientists have been involved in general project planning related to science. They have also attended many conferences such as the AAS meetings and helped to promote the Constellation-X science program and to get feedback during off-line splinter meetings.

SAO participated in setting up and promoting a Constellation-X Spectroscopy Work Shop at Columbia University. The workshop was open to the community, but attracted many FST scientists. An FST meeting was then held at Columbia immediately after the work shop to take advantage of the availability of a large number of FST scientists. Both the work shop and the subsequent FST meeting were highly successful in terms of attendance, spirited discussion, and identification of science needs and appropriate future actions. The combined workshop and FST meeting took place May 4 through May 8, 2003.

3.3 Top Level and Flow-down Requirements Definition and Error Budgeting

Drs. Bookbinder and Podgorski (both of SAO) took the lead role in coordinating and documenting what became the Constellation-X Top Level Requirements. Many scientists within the community participated in defining what the relevant requirements should be and many of the FST meetings were used for review of these requirements. Eventually, the FST, at least a majority of the members, endorsed these requirements and Dr. Bookbinder coordinated the Top Level Requirements Document which became a formal project document.

In order to apply these TLRs to the ongoing mission studies, Bookbinder and Podgorski worked to define the major flow-down requirements to be applied to the Constellation-X observatories and their related subsystems. These requirements were also published for review and comment and have become working documents.

Dr. Podgorski developed and maintained a number of error budgets in support of flow-down requirements definition. He also developed numerous error budgets for the SXT mirror assembly, for the OAP assembly and alignment and for the X-ray test verification at MSFC.

3.4 Mission Studies

SAO was continuously involved with the rest of the Constellation-X team in performing a variety of mission studies and related planning exercises. This work was ongoing due to a desire to develop increasing detail and also because of recurring and fairly significant changes to aspects of the overall Constellation-X configuration – frequently driven by somewhat external forces.

As noted above, the original concept for Constellation-X was to have six independent but essentially identical telescopes, each one on an independent satellite. Each telescope mirror assembly would have a focal length of 8.7 meters and an outer optic diameter of 1.2 meters. Many of the top level flow-downs were developed for this configuration. SAO led the work in developing these flow downs and was heavily involved in attitude control error budgets and determining timing requirements and evaluating systems for meeting those requirements.

A modest industry study was carried out by what was then TRW and also by Ball Aerospace. The thrust of the study was to evaluate the baseline configuration and, if appropriate, to propose alternative concepts. SAO had a lead role in defining the study SOW, helped provide liaison with the two industry teams, and was heavily involved in reviewing their final reports and recommendations.

Shortly thereafter, mainly because of perceived concerns about the long term viability of the Delta II rocket in terms of cost and availability, the configuration was changed to four telescopes, still on four separate satellites. SAO staff were heavily involved in modifying old studies and analyses to the new configuration and in extending the mission studies as resources permitted.

SAO support to Constellation-X mission studies continued throughout the program with emphasis on optical system performance, thermal control, science issues, and aspect and attitude control requirements.

3.5 TRIP Report

Beginning in November 2002 and extending into February 2003, SAO was heavily involved in an intense effort to respond to NASA Headquarters call for Technical Readiness and Implementation Plan (TRIP) report which was, in effect, a combination Phase A study and proposal effort. Tananbaum, Bookbinder, Podgorski, and Rasche worked closely with key GSFC project personnel. The work involved extensive travel, long hours, and extremely close and real time

coordination. SAO not only provided extensive inputs and plans, but helped to coordinate, edit, and negotiate the inputs of others.

The Constellation-X baseline at the time was the four mirror assembly – 1.6 meter outer diameter configuration. The contents of the report was defined by NASA Headquarters in terms of required subject material, page limits by section, numbers of pull-out pages, font size, and lines per inch. So, not only did the material have to be developed, but it had to be edited and fitted into the prescribed format.

Dr. Roger Brissenden (SAO) chaired a red team review that drew on experts from a number of organizations and was most helpful in focusing the TRIP effort.

Cost and schedule plans for flight mirror assembly (FMA) did not exist and had to be developed. Using an insightful analysis and plan for reflector fabrication developed by Heaney et al at Swales, Rasche (SAO) developed a complete plan. This plan included acquisition and manufacturing flow for mandrel productions. Close, cooperative, and responsive working meetings with Zeiss and to a lesser degree with Schott produced the needed information. A mirror build-up and test concept was defined and an integrated and detailed schedule and associated cost plan were developed.

Work began in November 2002. The report was delivered in February 2003 with a follow-up by the Headquarters review team in March.

One benefit of the TRIP exercise was that for the first time in the Constellation-X program, we had a detailed, comprehensive, and coherent technical and management plan. This point of reference was to serve the project well in the future.

3.6 Industry Liaison

It has been Constellation-X project policy to involve industry in studies and planning as early as possible consistent with available resources and the ability to define useful SOWs having a high probability of providing useful input and insight to the overall work. A corollary objective was to begin to establish interest on the part of various potential contractors as well as interpersonal relationships at the working level.

As mentioned earlier, two modest configuration industry studies were carried out comparatively early in the Constellation-X program. We found this and the subsequent planning for an SXT Flight Mirror Assembly (FMA) industry study to be valuable to the project independent from the actual study itself. That value came from preparing the SOW for the study procurement as well as for a pre-proposal industry briefing. This activity helped focus the Project Office on where we were, what we needed, and what we felt that industry could bring to the total activity in the context of limited resources.

We (GSFC and SAO) found that much of the industry interest involved key technical and management people with whom long standing ties were already in place. Many of these relationships derived the Chandra program where staff had interacted extensively and worked together on common problems. Also, relationships from HST were useful. This prior history of working together extended back at least twenty years in some instances and was of immeasurable value in communicating and understanding the challenges and requirements of Constellation-X.

Following the TRIP exercise, a substantial increase in project funding was expected and plans were made of an industry study related to the SXT FMA. A preliminary study by Swales related to reflector fabrication along with other material developed by GSFC and SAO was the basis for an industry briefing. The briefing was announced and held in July of 2003. Preparation of procurement documents continued into the Fall. This briefing material was a major effort and,

like the TRIP report, helped us to define both issues and expected flight program responsibilities.. By that time industry teams had been formed both for developing the FMA and for bidding as prime contractor for the total Constellation-X flight program. SAO took the lead in much of the discussion and interaction that took place during this period.

In spite of an extremely well-received TRIP report, the expected augmentation in funding to Constellation-X did not materialize. This became clear in the Fall of 2003. As a consequence, the plan to start FMA industry studies was put on hold indefinitely. One unfortunate result of this was that corporate interest in Constellation-X gradually began to erode and teams that had been gathered to support the studies were disbanded and reassigned to more pressing work.

Nonetheless, contacts were maintained among key people on the Constellation-X team and their personal contacts in industry. The object of these informal interactions was to keep the industrial organizations aware of program status and developments and to promote and maintain at least some interest in our program. All of the major organizations recognized these points of contact and supported this informal liaison.

3.7 Collaboration Considerations

A possible collaboration was considered between NASA and ESA. The thought has been to meet most of the objectives of the ESA XEUS program and the NASA Constellation-X program with a single combined mission. Recent activity is discussed in Section 2.5.5. We note here that other exploratory talks took place earlier, but at that time, little interest was shown by the Europeans in such a collaboration. Drs. Tananbaum (SAO) and White (GSFC) were involved in these earlier discussions and are taking the lead as well in the current talks and negotiations.

4.0 List of Reports and Publications

4.1 Annual and Supplementary Reports

Annual and Supplementary Reports submitted under the Agreement are listed below. From time to time, Supplementary Reports were required to ensure the steady flow of funding. This was usually due to slip between end of funding and the formal end of the Agreement calendar year. GSFC requires a proposal that is current within six months to fund against. The reports are listed together with additional date information in Table TBD

Report Type	Period Covered	Date Submitted
Annual #1	10/1/98 - 9/30/99	2/18/00
Annual #2	10/1/99 - 9/30/00	10/2/00
Supplement to #2	10/1/00 - 1/31/01	2/8/01
Annual #3	10/1/00 - 9/30/01	2/22/02
Supplement to #3	8/1/01 - 1/10/02	2/22/02
Annual #4	10/1/01 - 9/30/02	5/13/03
Supplement to #4	10/1/02 - 3/13/03	8/25/03
Annual #5	10/1/02 - 9/30/03	5/20/04
Final Report (this document)	10/98 – 10/04	

4.2 Publications

Many papers were prepared and presented. Most of them were joint papers, usually with a combination of SAO, GSFC, and MSFC authors. Listed below are papers in which an SAO person was one of the principal authors. SAO staff appeared as co-authors on an additional nine papers/presentations.

Paul Reid, Robert Cameron, Lester Cohen, Martin Elvis, Paul Gorenstein, Diab Jerius, Robert Petre, William Podgorski, Dan Schwartz, and William Zhang, "Constellation-X to Generation-X: Evolution of large collecting area, moderate resolution grazing incidence x-ray telescopes to larger area, high resolution, adjustable optics", *SPIE Proc.* *5488*, 325 (2004).

William A. Podgorski, Jay Bookbinder, David A. Content, William N. Davis, Mark D. Freeman, Jason H. Hair, Scott M. Owens, Robert Petre, Paul Reid, Timo T. Saha, Jeffrey W. Stewart, and William W. Zhang, "Constellation-X spectroscopy x-ray telescope optical assembly pathfinder image error budget and performance prediction", *SPIE Proc.*, *5168*, 318 (2003).

William A. Podgorski et al, "Constellation-X Spectroscopy X-Ray Telescope and Assembly and Alignment, SPIE Conference August 2002.

N. White, H. Tananbaum, S. Kahn, "Next Generation of X-Ray Observatories", *Workshop Proceedings, Leicester X-ray Astronomy Group Special Report XRA97/02*, (eds. M. Turner & M. Watson) p. 173

N. White, H. Tananbaum, S. Kahn, "The High Throughput X-ray Spectroscopy (HTXS) Mission", in *Next Generation of X-ray Observatories (1997)*

H. Tananbaum, "Workshop Summary and Future HTXS Plans" in *Proceedings of the High Throughput X-ray Spectroscopy Workshop - Harvard-Smithsonian Center for Astrophysics*, (ed. H. Tananbaum, N. White, P. Sullivan); p. 336 (1997)

N. White and H. Tananbaum, "The Constellation X-ray Mission", presented at The 3rd Integral Workshop *{The Extreme Universe, Taormina, Sicily, September, 1998}*

N. White and H. Tananbaum, "The Constellation X-ray Mission", *Astron. Nach.* 320, 280, 1999.

H. Tananbaum et al, "Constellation X-ray Mission: Implementation Concept and Science Overview", *Proc. SPIE Vol. 3765*, 62-72 *{EUV, X-ray and Gamma-ray Instrumentation for Astronomy X}*, (eds. O Siegmund, K. Flanagan).

N. White and H. Tananbaum, "The Constellation X-ray Mission", *X-ray Astronomy: Stellar Endpoints, AGN and the Diffuse X-ray Background*, (eds. N. White, G. Malaguti, G. Palumbo), *AIP Conf. Proc.* 599, 1027 (2001)

N. White and H. Tananbaum, "The Constellation X-Ray Mission", *ApJ&C* 39, 465 (1999)

N. White and H. Tananbaum, "The Constellation X-ray Mission, *Large Scale Structure in the X-ray Universe*", *Proceedings of the 20-22 September 1999 Workshop*, Santorini, Greece (eds. M. Plionis & I. Georgantopoulos) Atlantisciences, Paris: p. 287

N. White and H. Tananbaum, "The Constellation X-ray Mission", *Highly Energetic Physical Processes and Mechanisms for Emission from Astrophysical Plasmas*, *Proceedings of IAU Symposium #195*, 6-10 July 1999: Astronomical Society of the Pacific, p. 61

N. White, J. Bookbinder, and H. Tananbaum, "The Constellation X-ray Mission" *X-ray Astronomy 2000 Palermo*, ASP Conf. Ser. 234, 2001, p. 597 (eds. R. Giacconi et al)

N. White and H. Tananbaum, "The Constellation X-ray Mission", *New Century of X-ray Astronomy*, ASP Conf. Proc. 251, 224 (eds. H. Inoue and H. Kunieda) (2001)

N. White and H. Tananbaum, "The Constellation X-ray Mission", *X-ray Astronomy: Stellar Endpoints, AGN and the Diffuse X-ray Background*, (ed. N. White et al), AIP Con. Proc. 599, 1027, (2001)

N. White and H. Tananbaum, "Constellation-X Mission: Science Objectives and Implementation Plan", *X-ray and Gamma-Ray Telescopes and Instruments for Astronomy*, (eds. J. Truemper, H. Tananbaum), SPIE 4851, 293, (2003)

H. Tananbaum, N. White, and J. Bookbinder et al, "Constellation X-Ray Mission: recent developments for mission concept and technology development", SPIE 5488, 492-504 (2004).

N. White, H. Tananbaum, K. Weaver et al, "The science goals of the Constellation-X Mission" SPIE 5488, 382-387 (2004)